THERMAL AND OPTICAL CHARACTERIZATION OF PARABOLIC TROUGH RECEIVERS AT DLR'S QUARZ CENTER – RECENT ADVANCES

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Abstract

The performance of a parabolic trough receiver can be described by two parameters, the specific heat loss at operating temperature and the optical efficiency. DLR operates two test benches for the measurement of these parameters with high accuracy in its QUARZ Center. In the heat loss test bench THERMOREC the receiver is electrically heated to operating temperatures. In a steady state of constant heating power and absorber temperature an energy balance equation yields the thermal losses. Recent work was dedicated to the introduction of end heaters which lead to a significantly more even absorber temperature profile. Furthermore brass is now used for the homogenization tube with far reduced oxidation at the tube surface compared to the formerly used copper. In the ELLIREC, the linear focus test bench for the measurement of optical efficiency, the receiver is irradiated with solar simulator lamps. The enthalpy increase of cooling water flowing through the receiver at ambient temperature indicates the optical efficiency. The test bench has been characterized for reproducibility to 1 σ = 0.25% and homogeneity of the incident radiation in the linear focus to ± 5 % of the average. By comparison of the enthalpy increase to that of the defined reference receiver DLR 70-1 the relative optical efficiency is determined.

Keywords: parabolic trough receiver, optical efficiency, thermal loss power, laboratory test bench

1. Introduction

The receiver is a central part in every concentrated solar power plant. Due to the advanced market and nature of the technology, in large parabolic trough plants the receiver can be regarded a standardized product with defined dimensions and various available manufacturers. In DLR's QUARZ Center two laboratory test benches are operated to characterize the optical efficiency $\eta_{opt,geo,rec}$ and the heat loss power $P_{th,loss}$, the two key parameters of parabolic trough receivers.

The energy balance in a parabolic trough collector can be described [1] as

$$P_{coll} = \eta_{opt,geo,rec} * P_{in} - P_{th,loss} , \quad (1)$$

where P_{coll} is the enthalpy increase in the heat transfer fluid flowing through the receiver and P_{in} is the power of the concentrated radiation intercepted by the receiver.

The heat loss power $P_{th,loss}$ of a modern receiver with well evacuated annulus primarily depends on the absorber temperature T_{abs} of the receiver, the emissivity of the absorber coating, and the tube diameter. The influence of ambient conditions like ambient wind speed and ambient temperature influence the heat loss only in the order of a few percent of the total heat loss [2].

The optical efficiency is dependent on transmittance τ of the glass envelope, absorptance of the absorber tube α, and the net area factor ψ. As the geometric effects at the bellows are included in the optical efficiency here, it is also called opto-geometric efficiency $\eta_{opt,geo,rec}$. The optical efficiency can be expressed in a first approximation as a product $\eta_{opt,geo,rec} \approx \tau\ \alpha\ \psi$. A more accurate description includes effects of multiple reflections and incidence angle effects.

At DLR's QUARZ Center test benches for the measurement of both the opto-geometric efficiency and the heat loss are available. The measurement of both parameters is advisable, as the manufacturers can optimize one parameter at the expense of the other. This paper presents the current testing procedures of both test benches with an emphasis on recent developments.

2. Heat Loss Testing

Heat loss testing of parabolic trough receivers has become a standard laboratory measurement technique. It is applied in measurement institutes like NREL, CENER and DLR but also in industry [3], [4]. A first round robin test for the comparison of test benches of three participating partners was performed in 2009; the results were presented at last years SolarPACES Conference [3] and showed a good agreement with maximal deviations of 10 %.

In thermal loss testing the receiver is heated electrically to operating temperature. In the steady state of constant heating power and constant temperature the heating power minus parasitic losses indicate the heat loss of the receiver at the respective absorber temperature. For the electrical heating two methods are common. Either electrical heating elements are inserted into the absorber tube (often a homogenization tube of copper is used to even the temperature profile of the absorber in longitudinal and vertical direction), or heating is performed by direct joule heating of the steel absorber tube that functions as the resistor for the resistance heating. Temperature measurement of the absorber tube is usually performed by thermocouple measurement at the inside surface of the absorber tube. Sometimes absorber tube elongation is used for the temperature measurement, however the steel type and the respective heat expansion coefficient have to be known with sufficient accuracy [3].

The heating concept of the THERMOREC is shown in Figure 1. The bulk of the heating power is delivered by the main heater. It is 4060 mm in active length and provides constant heating power per unit length. It is surrounded by a homogenization tube (not shown in the figure) of copper or brass. While the heat conductivity of brass is lower than that of copper, the handling of brass is much easier as its tendency to oxidation at the surface is lower at typical testing temperatures of up to 400 °C. At the ends thermal insulation minimizes thermal losses via the end faces. As these losses cannot be eliminated entirely by insulation, end heaters are used and controlled in order to achieve an even absorber temperature profile.

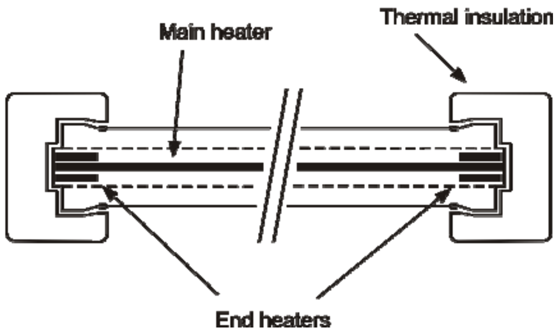

Figure 1: Heating concept of THERMOREC with main heater, end heaters and thermal insulation, chosen system borders exclude bellow losses

The energy balance equation in the steady state is

$$P_{\mathrm{th,loss}} = P_{\mathrm{main}} + P_{\mathrm{end}} - P_{\mathrm{ax,loss}}, \qquad (2)$$

where P_{main} is the electrical heating power of the main heater. P_{end} is the power of the end heaters. Its contribution is typically < 5 % of the total heating power. $P_{ax,loss}$ is the loss power leaving the receiver via the thermal insulation. This correction is at the order of 2 % to 4 % of the overall heat loss. $P_{ax,loss}$ is calculated using the surface temperatures of the thermal insulation surfaces considering free convection and radiation.

Typically bellow losses are excluded from heat loss measurement at the THERMOREC by insulating the bellow surface up to the glass-to-metal seal, as shown in Figure 1, however measurements can also be performed with the original bellow insulation mounted.

16 internal type-N thermocouples are used which measure the temperatures of the absorber and homogenization tube. Thermocouples for the measurement of the absorber are mounted on the brass tube and pressed against the absorber inner surface with spring leafs. Thermocouples are mounted at multiple longitudinal positions and face directly up- and downward in order to measure the temperature of the absorber side facing up- and downwards. Hence the temperature is monitored in longitudinal and vertical direction. The mean temperature T_m is calculated according to $T_m^4 = \Sigma T_i^4 f_i$, where each measured temperature T_i to the 4th power is weighted with a corresponding factor f_i that expresses the attributed fraction of the absorber surface $f_i = A_i / A_{abs}$. The corresponding surface A_i is typically half the circumference – as there are thermocouples for the upper and the lower side of the absorber – times the corresponding length, which is the sum of half the distances to both nearest neighbors.

Currently the THERMOREC is operated by application of a constant heating power. After 5 to 8 hours – depending on the heating power and the quality of the receiver - a quasi steady state is reached. It is planned to implement a PID-control-loop for faster operation in the future, however the current heating mode has the advantage, that for all thermocouples an exponential fit in the form of $T(t) = T_\infty$ (1-exp(t/τ)) with the fitting parameters T_∞ and τ is possible, if the data range is properly chosen. T_∞ then yields a prediction for the steady state temperature and hence an assessment of the quality of the steady state and potential correction value. Typically T_∞ differs only 0.2 K from the measured mean absorber temperature after 5 to 8 hours.

An error calculation of the absorber temperature measurement that includes the uncertainties of the thermocouple, the thermocouple data acquisition and the steady state quality yields an uncertainty of ± 1.3 K. However, a major uncertainty arises from the question of the quality of the thermal contact of the thermocouple to the absorber tube: As the thermocouple is situated between absorber tube and the homogenization tube, that is 10…40 K hotter than the absorber, it is unclear how well the thermocouple temperature is in agreement with the absorber tube temperature, which is actually intended to be measured. Although the thermocouple is pressed on the absorber by spring leafs, radiation from the homogenization tube and hot air from convection from the homogenization tube and heat conduction via spring leafs and thermocouple cables do also heat the thermocouple. Currently there is no good basis for an estimation of the additional uncertainty. The authors believe it could easily exceed the above stated uncertainty of the thermocouple measurement and hence dominate the overall uncertainty. Furthermore this effect leads to a systematical overestimation of the absorber temperature. The uncertainty in power measurement, including main heater power, end heater power and axial loss power has been calculated to ± 0.5 % at 800 W heating power.

As the introduction of end heaters has been a recent change to the THERMOREC test bench, in Figure 2 example measurements of the absorber temperature profile are shown with and without activated end heaters. Although the end losses via the insulation amount for only 2 % to 4 % of the total heating power, a distinct temperature profile emerges, if only the main heater is used. At the temperature level of 300 °C the temperature difference from center to the ends amounts to approximately 30 K. By using the end heaters the homogeneity is vastly improved. At a mean value of approximately 350 °C deviations are in the order of ± 3 K. These deviations are dependent on the calibration of the thermocouples, the homogeneity of the pressing force of the spring leafs and the homogeneity of the absorber coating itself. Thermocouples with vastly reduced spring force or without any contact to the absorber at all can be detected by their significantly higher temperature levels and are excluded in the evaluation process.

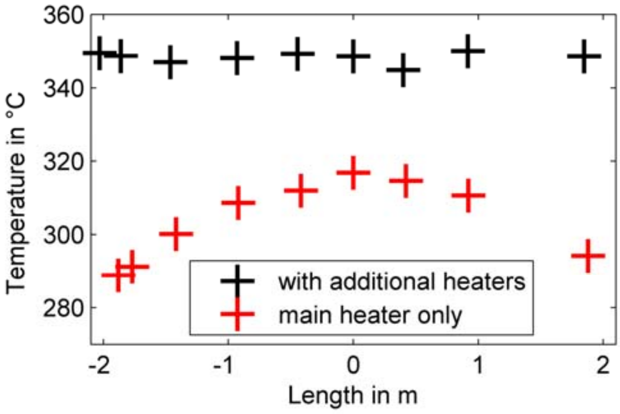

Figure 2: Distribution of absorber temperature in longitudinal direction with and without end heaters

3. Optical Efficiency Testing

2.1. Experimental Setup

The ELLIREC test bench is a solar simulator test bench for the optical characterization of linear focus receivers like parabolic trough receivers. Optical characterization is performed by measuring the enthalpy increase P_{coll} (compare equation 1) of water at ambient temperatures through the receiver. Hence the optical properties are measured as the opto-geometric efficiency $\eta_{opt,geo,rec}$, that combines glass transmittance τ, absorber absorptance α, and net area factor ψ [1],[5]. The linear focus is achieved by an elliptical cylinder reflector geometry with flat end mirrors, while the metal halide lamps at two positions and the receiver are situated in the respective focal lines, compare Figure 4. Typical measurement conditions are the operation of four lamps with 13 kW_e in total, a volume flow of 0.850 m^3/ h, and a temperature increase of 3-4 K resulting in an enthalpy increase P_{coll} = 4.5 kW. P_{coll} is considered to be equal to the absorbed power as thermal losses are neglected. The Reynolds number is in the transitional range of 3000…4000.

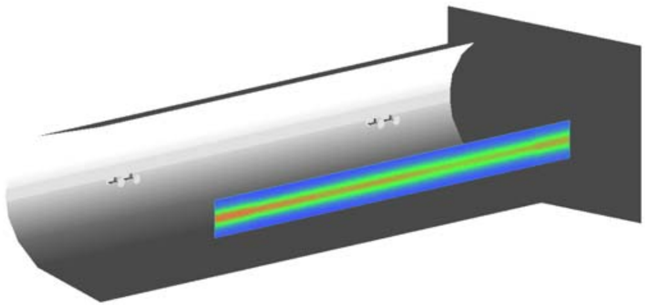

Figure 3: Geometry of the ELLIREC test bench: Elliptical trough with flat end mirrors. Length 5.0 m, semi-major axis 1.0 m, semi-minor axis 0.7 m. At the place of the receiver a flat target displaying the irradiance distribution in the focal line of the receiver is shown. For illustrative purposes the reflector is cut open, in reality the mirrors fully enclose lamps and receiver;

Reproducibility of the enthalpy increase measurement has been investigated and was found to be ± 0.25 % (1 σ) as determined with 17 independent measurements. This figure includes stability of receiver mounting accuracy, radiant flux of the lamps, temperature and flow measurement, mirror shape accuracy, and cleaning over a period of few months.

2.2. Optical characterisation as relative measurement and definition of master standards

According to Equation 1, the opto-geometric efficiency of the receiver at ambient temperature is defined as $\eta_{opt,geo,rec} = P_{coll} / P_{in}$. Since the incident flux on the total receiver length P_{in} is not exactly known for the test bench, the test bench is used for relative measurements of different receivers. As the measurement is performed at ambient temperatures, an analysis of the bellow design and a correction including the absorber expansion is necessary. In order to provide a long term stable absolute reference DLR has defined two reference receivers DLR70_1 and DLR90_1 for the two receiver geometries of 70 mm and 89 mm diameter. As the used receivers are state of the art receivers, the measured enthalpy increase is multiplied by an anonymization factor.

2.3. Investigation of geometrical radiation distribution

The flux distribution along the receiver length has to be homogenous, if the receiver aperture is to be included in the optical performance characterization. Applying the camera target method [6] the radiation distribution along the focal line was measured. The flat target was oriented as shown in Figure 4. Measurements confirmed the prior ray tracing simulations by showing a nearly flat distribution with about 10 % higher flux near the bellows. The width of the focus as measured on the target is in the order of 10 cm FWHM. In Figure 4 the flux distribution on the circumference of the receiver as simulated for the ELLIREC is compared to Eurotrough data showing a-one-lobe distribution instead of the two lobes at the Eurotrough. As typical parabolic trough receivers are nearly axi-symmetric and blocking elements like evacuation nipple or getters are turned to the 180°-position for the measurement, this is considered negligible.

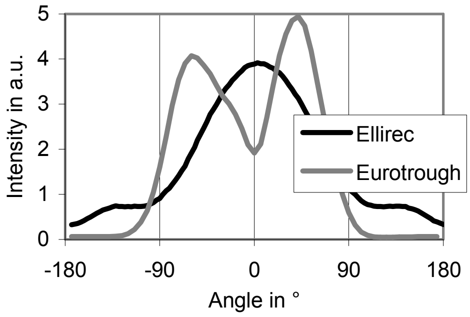

Figure 4: Simulated flux distribution on the circumference of the receiver in the ELLIREC test bench compared to Eurotrough data

5. Conclusion

The two test benches for the measurement the specific heat loss at operating temperature and the characterization of the optical efficiency of parabolic-trough receivers have been qualified in detail. Both tests are in use for standardized measurements of such receivers from series production or new developments. The electrical heating with heater inserts in the heat loss test bench THERMOREC leads to very good accuracy of the power measurement and a relatively flexible testing. In a steady state of constant heating power and absorber temperature an energy balance equation yields the thermal losses. End heaters have been added, leading to a significantly more homogeneous absorber temperature profile in the tests. The test bench for the measurement of optical efficiency ELLIREC has been characterized for reproducibility to $1\ \sigma = 0.25$ % and homogeneity of receiver incident radiation to ± 5 % of the average. Test results from this optical test bench do not provide an absolute value. A standard reference test sample has been introduced that allows determination of results relative to the DLR 70-1 reference sample.

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